PHYS 393
Low Temperature Physics
Set 3:

Superconductivity – part 1

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Superconductivity outline

Essentials only in PHYS393

- This set:
  - Experimental results
  - Deductions
- Next sets:
  - Theory
  - Flux quantization
  - Type I / Type II superconductors
  - New materials

90 years of superconductivity

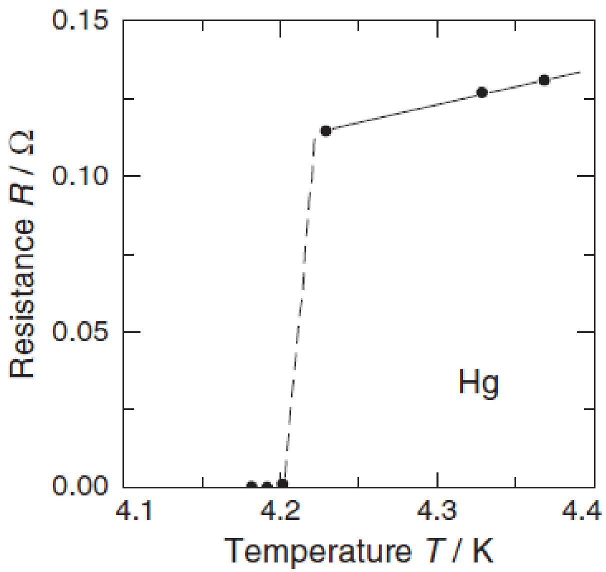
- Discovered in 1911 by K. Onnes in pure metals (first observation in Mercury at 4.2K)
- Discoveries and model development for 50 years

- 1957, BCS: microscopic theory of superconductivity by Bardeen, Cooper, Schrieffer (Nobel Prize 1972); Cooper pairs

- High-T_C superconductors: new era since 1986, T_C from 30K to 135K; still not understood well

Experimental results (I)

- Electrical conductivity falls practically to zero below critical temperature T_c
- Decay of *persistent shielding current* shows drop of R by at least 16 orders of magnitude
- Demonstrates that R=0 for $T < T_c$



Discovery of Superconductivity

Experimental results (II)

- See table for T_c of metals under atmospheric pressure
- Metals with good normal state electrical conductivity do not show superconductivity (Cu, Ag, Au, Na, K)
- Ferromagnets (Fe, Ni) do not exhibit superconductivity

Element	T_c (K)	Element	T_c (K)	Element	T_c (K)
Al	1.19	Nb	9.2	Tc	7.8
Be	0.026	Np	0.075	Th	1.37
Cd	0.55	Os	0.65	Ti	0.39
Ga	1.09	Pa	1.3	Tl	2.39
Hf	0.13	Pb	7.2	U	0.2
Hg	4.15	Re	1.7	V	5.3
In	3.40	Rh	0.0003	W	0.012
Ir	0.14	Ru	0.5	Zn	0.9
La	4.8	Sn	3.75	Zr	0.55
Mo	0.92	Ta	4.39		

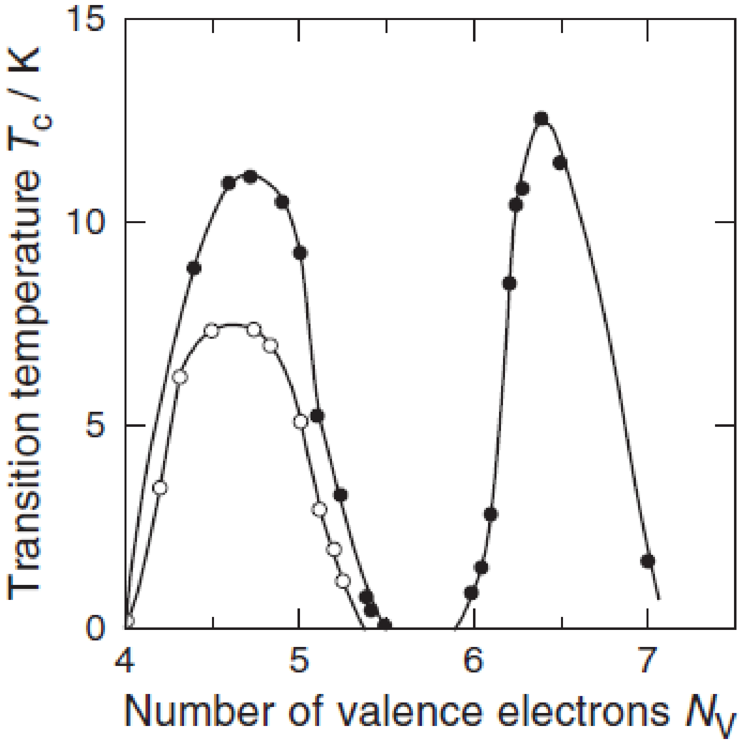
Experimental results (III)

- See table for T_C of compounds under atmospheric pressure
- Material structure (crystals, alloys, amorphous metals) is not important
- Pressure sometimes enables superconductivity
- Magnetic impurities (but no other type) affect superconductivity
- Compounds become superconductive although they may contain elements that don't

Compound	T_c (K)	Compound	T_c (K)	Compound	T_c (K)
Nb_3Sn	18.1	MgB_2	39	UPt_3	0.5
Nb_3Ge	23.2	$PbMo_6S_8$	15	UPd_2Al_3	2
Cs_3C_{60}	19	YPd_2B_2C	23	$(TMTSF)_2ClO_4$	1.2
Cs_3C_{60}	40	$HoNi_2B_2C$	7.5	$(ET)_2Cu[Ni(CN)_2]Br$	11.5

Superconductivity and atomic structure

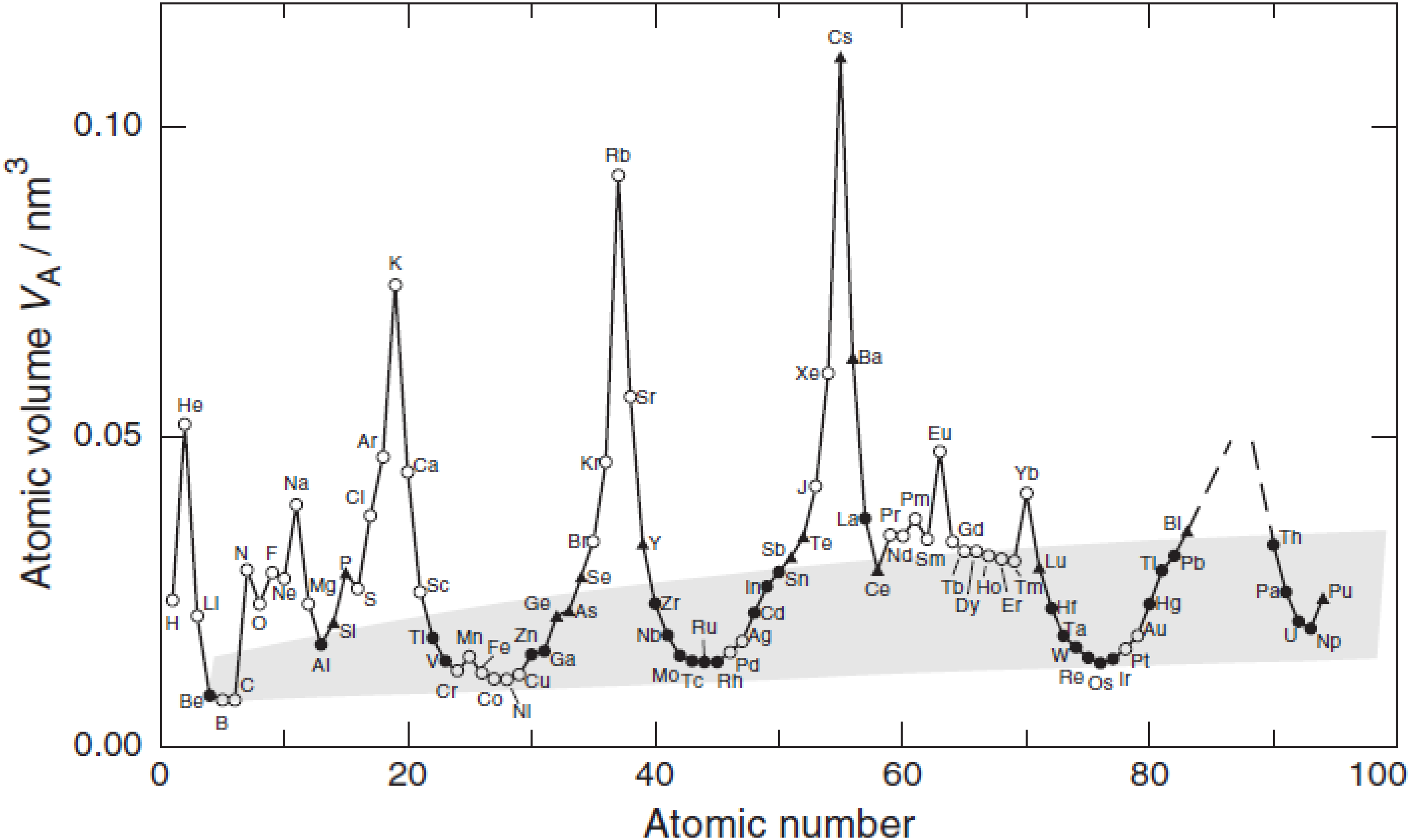
- Small atomic volume favours superconductivity (see graph on next page)
- High pressure (which causes decrease of atomic volume) favours superconductivity (semiconductors like Si, Ge become superconductive under high pressure)
- *Matthias rule*: mean number of valence electrons affects superconductivity



T_C vs mean number of valence electrons for two series of alloys (Zn-Nb-Mo-Re full circles, Ti-V-Cr open circles)

Superconductivity and atomic volume

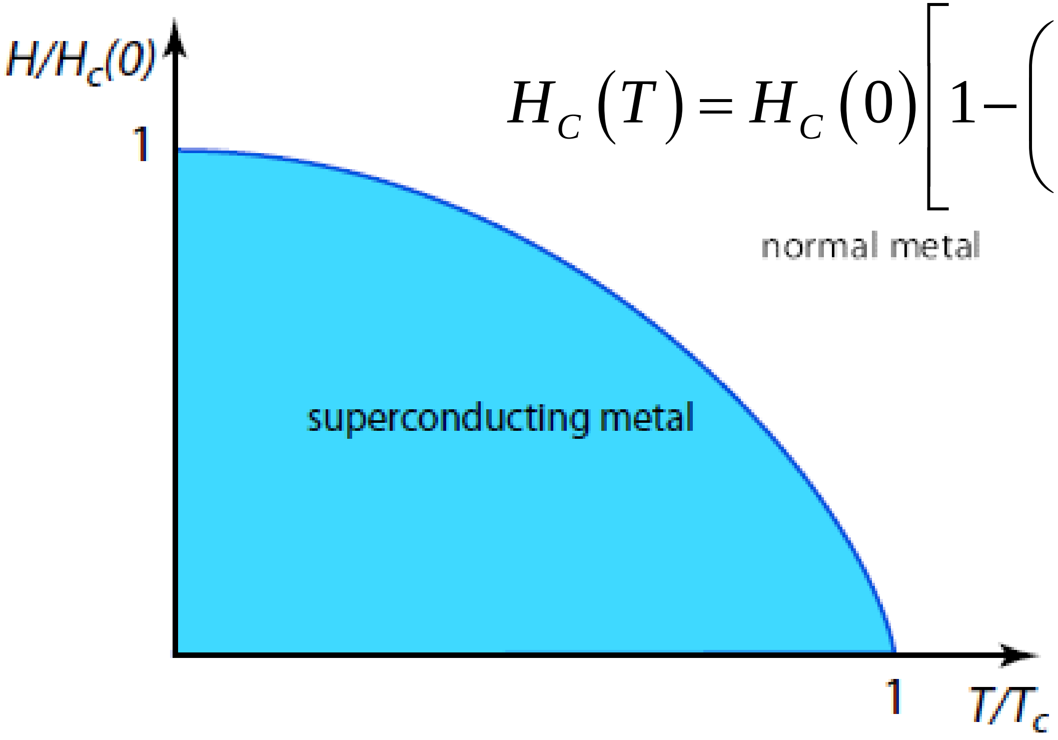
Atomic volume of elements versus atomic number. Full circles: superconductors. Open circles: normal conductors. Triangles: superconductors under pressure. Shaded area: region where main superconductors are found



Effect of magnetic field – Critical Field

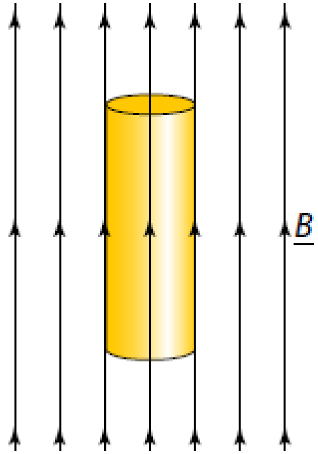
- Magnetic field destroys superconductivity
- Critical Field: for temperature $T<T_C$ the transition between normal and superconducting states takes place at field $H_C(T)$ called Critical Field:

$$H_C(T) = H_C(0)\left[1-\left(\frac{T}{T_C}\right)^2\right]$$

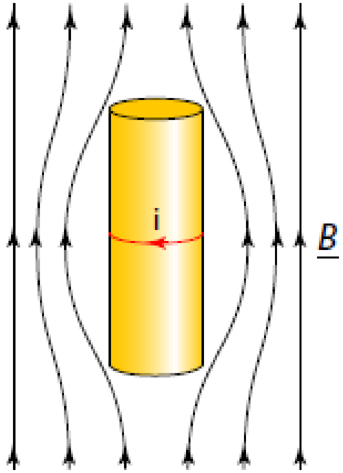


Meissner-Ochsenfeld Effect

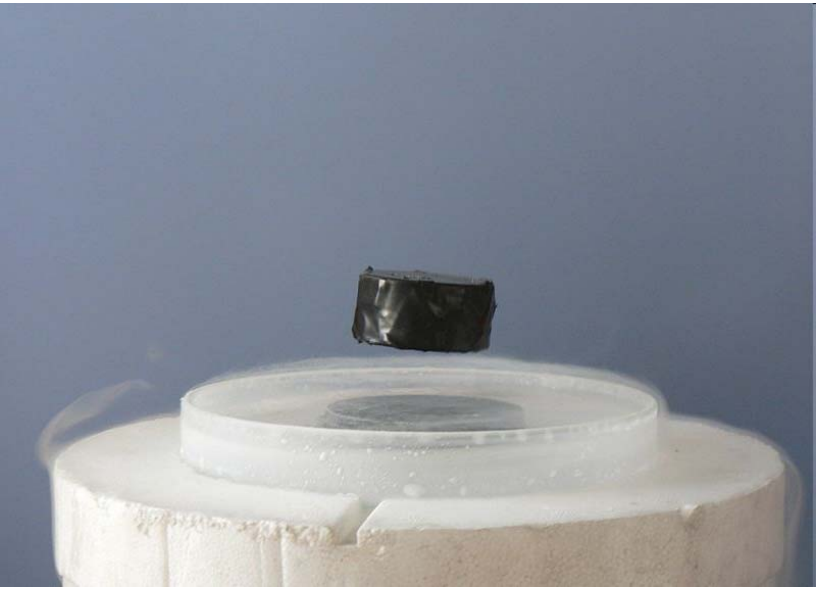
- Magnetic field $H<H_c$ applied to cylindrical sample
- Sample cooled to below T_c
- Superconducting state expels all magnetic flux from sample volume
- No simple consequence of zero electrical resistance
- Discovered in 1933
- Magnetic levitation



Normal conductor



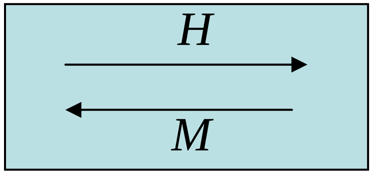
Superconductor



Magnet levitating
above superconductor

Perfect diamagnetism

In superconductive volume:



Applied field

$$\vec{B} = \mu_0\left(\vec{M} + \vec{H}\right) = 0 \Rightarrow \vec{H} = -\vec{M}$$

Sample magnetization

No flux inside sample

$$\chi = \frac{M}{H} = -1$$

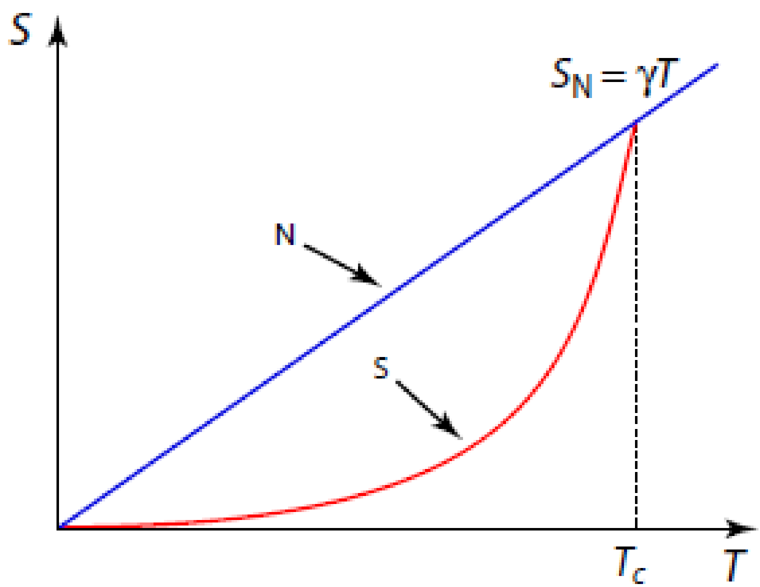
magnetic susceptibility

χ=-1 defines perfect diamagnet

- Flux exclusion due to superconducting current flow around the surface
- Current and field exist within penetration depth (typical 50nm) inside superconducting volume

Superconductor heat capacity

- Two contributions in heat capacity
  - Lattice vibration: same for normal and superconducting states; ignore in following
  - Electron energy distribution
- Normal state can be measured below T_C by applying field $H>H_C$



Entropy S vs T for normal (n) and superconducting (s) states

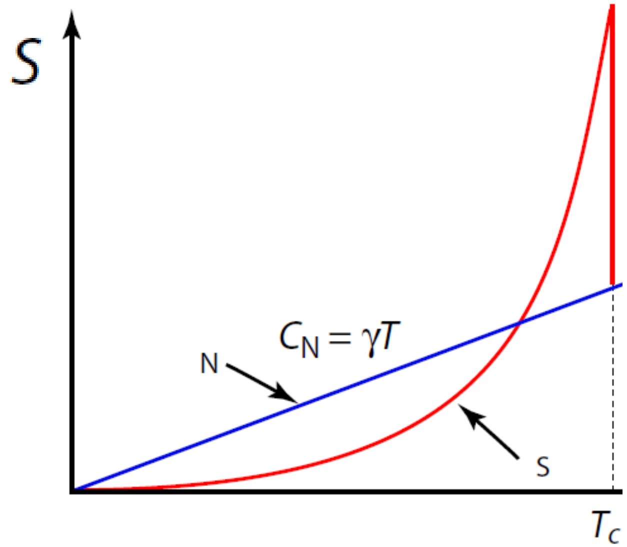
Superconductor heat capacity

Superconducting heat capacity:

$$C_V = A\gamma T_C e^{-\frac{\alpha T_C}{T}}$$

Where γ is constant for normal heat capacity

A, α constants for material



$$C_V = T\left(\frac{dS}{dT}\right)$$

Entropy S vs T for normal (n) and superconducting (s) states

Superconductor heat capacity

if we set $\Delta = 2\alpha k T_C$

we get $C_V \propto e^{-\frac{\Delta}{2kT}}$

implying energy gap Δ between ground and excited states of electrons in superconducting state

- Shape (red curve, previous page) reminds of exponential rise in C_V of He^4 at $T<T_C$
- Suggests two-component model like He^4

Two component model

In superconductor

- Supercurrent: flows without resistance (like superfluid); carries no entropy; has no contribution to heat capacity
- Normal current: flows with resistance (like normal fluid in liquid He II)

Proportion of each component governed by energy gap for $T<T_C$:

$$n \propto e^{-\frac{\Delta}{kT}} \qquad\qquad s \propto \left(1-e^{-\frac{\Delta}{kT}}\right)$$

Experimental results suggest that $\Delta(0)\sim 3kT_C$ varying to $\Delta(0)\sim 3kT_C$

Puzzling: How can the behaviour of a superconductor (carriers electrons: fermions) be similar to superfluid He4 (atoms are bosons)?

The answer is in the BCS theory, see next part of notes